Sixth International Symposium on Aviation Psychology. April 29-May 2, 1991, Columbus, Ohio

WHO OR WHAT SAVED THE DAY?
A COMPARISON OF TRADITIONAL AND GLASS COCKPITS

Asaf Degani
San Jose State University Foundation
and NASA Ames Research Center
Moffett Field, CA

Sheryl L. Chappell
NASA Ames Research Center
Moffett Field, CA

Michael S. Hayes
Air Line Pilots Association
Herndon, VA

ABSTRACT

This study examined incidents reported to NASA's Aviation Safety Reporting System from a novel perspective: rather than focusing on the factors contributing to or causing incidents, this study concentrated on *who* and *what* (subsystems and information) enabled the recovery from an anomaly. Incident reports describing altitude deviations were classified as to cockpit type (glass or traditional), flight phase, agent restoring safety, and cockpit subsystems providing specific information that helped restore safety. The data revealed and quantified the agents, information, and factors that "saved the day." The flight crews used many sources of information to detect the altitude deviations: altimeter, outside scene, altitude alert, kinesthesia, attitude, and communications monitoring. In the glass cockpits the crews also used the map display and autothrottles to detect deviations from assigned altitudes. There was an interaction between the person detecting the anomaly (controller/flight crew) and the type of cockpit. Glass cockpit flight crews detect proportionally more deviations than their counterparts in traditional cockpits, while controllers tend to detect more deviations involving traditional cockpits. There was no effect of cockpit position (captain/first officer). A model that details the flow of altitude information between air traffic control, flight crews, and cockpit subsystems was developed and validated. This model identifies strengths and weaknesses in the flow of altitude information within the current ground/air system.

INTRODUCTION

A considerable amount of research has identified and quantified the factors that generate aviation incidents (Billings & Cheaney, 1981; Degani & Wiener, 1990; Lyman & Orlady, 1981; Monan, 1979, 1988; Orlady, 1982). This paper takes a somewhat novel approach for studying aviation safety: instead of concentrating on the factors that led to the incident, we focused on *who* and *what* prevented it from progressing to an accident. Specific information provides the necessary "trigger" for the agent to detect the anomaly, thereby breaking the chain of events leading to an unsafe situation (Schwartz, 1990). Many of the incidents reported to the National Aeronautics and Space Administration's (NASA) Aviation Safety Reporting System (ASRS) reveal who and what "saved the day." Detection and successful recovery can result from many types of anomalies. In this study, however, we focused on the detection of altitude deviations.

Altitude deviations are one of the most prevalent aviation safety problems reported to the ASRS program (Thomas & Rosenthal, 1982). Altitude deviations create a potential for mid-air collisions, controlled flight into terrain, and related events such as passenger and crew injuries due to rapid flight maneuvers (Billings, Grayson, Hecht & Curry, 1980; Sumwalt, 1991; Wiener, 1977). When deviations occur, the redundancies and feedback loops embedded in the system often allow the flight crew and/or the controller to detect and correct the situation (NASA, 1978). For example, an air traffic controller may detect that a flight crew member has responded to a clearance addressed to another aircraft, or a pilot may detect an incorrect entry in the flight guidance system. In the current ground/air system, dedicated mechanisms detect anomalies by monitoring and alerting operators to an unsafe condition. For example, altitude alerters in the aircraft and the air traffic control Operational Error Detection Program are subsystems designed to inform operators that an aircraft is deviating from an assigned altitude.

Advancement in technology constantly changes the way pilots fly their aircraft, as well as the presentation of flight information. For example, the introduction of the automatic flight system and the flight management computer (FMC) has changed the manner of controlling vertical and lateral navigation. In addition, the Electronic Flight Instrument System and its glass displays have dramatically changed the level of information processing and presentation of navigational data in modern cockpits (Wiener, 1989). Therefore, information that "triggers" detection of an anomalous situation, e.g., an altitude deviation, may differ in glass-cockpit aircraft such as the Boeing 757/767, Douglas MD-88, and Airbus A-310/320. Glass cockpits contain features that enable software designers to define, and flight crews to modify and "build" descent profiles long before the path is flown. In contrast, most traditional cockpits, such as the Boeing 727, Douglas DC-9, Airbus A-300, etc., usually present "raw" and/or instantaneous information for navigation (with exception of area navigation equipment). Traditional cockpits do not contain systems that permit a change in vertical flight path in the future.

ASRS incident reports describing deviations from assigned altitude were analyzed in order to address three questions:

1. Who were the agents that detected the altitude deviation?

2. What kind of information and what type of subsystems provided the triggers for detection of such anomalies?

3. Did the agents, subsystems, and type of information vary between traditional and glass cockpits?

Another goal of the study was to develop an information flow model for altitude information and to identify some of the links, redundancies, and feedback loops within the current ground/air system.

METHOD

Strategy for Selection of Incident Reports

The sample consisted of 500 ASRS reports from air carrier pilots detailing altitude deviations (NASA, 1991). These were the most recent reports in the ASRS database at the time of the search (January, 1991). The sample consisted of two mutually exclusive datasets: traditional cockpits (250 reports) and glass cockpits (250 reports). The glass-cockpit dataset contained reports of cockpits equipped with both FMCs and Electronic Flight Instrument Systems, thereby excluding aircraft such as the MD-80. We also attempted to exclude from the glass-cockpit dataset any reports involving the B-747/400, MD-11, or the A-310/320 aircraft, since these glass-cockpit aircraft utilize a tape altimeter; we were concerned that this would confound some of the triggering information. All aircraft, in both datasets, had a gross weight of over 60,000 pounds.

Taxonomy and Screening of Incident Reports

The reports were coded according to the following categories:

1. *Cockpit type*: traditional, glass

2. *Flight phase*: departure (takeoff to top of climb), cruise, descent (top of descent to 10,000 feet), approach (10,000 feet to landing)

3. *Agent restoring safety*: "duty" (controller, pilot flying, pilot not flying, flight engineer), "position" (captain, first officer, second officer)

4. *Information or subsystem* that helped restore safety.

While the first two categories were easily obtained from the report header, the latter two categories were much more difficult. Sometimes these categories had to be inferred from the report narrative. The analysis and coding was done by an experienced airline pilot. The first 300 reports were submitted for two independent analyses to ensure quality control.

In this paper, an altitude deviation was said to occur when the aircraft was inadvertently flown at an altitude different from what was intended by the Air Traffic Control (ATC) system. A considerable number of reports were excluded due to insufficient information to infer the agent detecting the anomaly or the triggering factor(s). We also excluded reports pertaining to altitude excursions due to encounters with turbulence and excursions resulting from the exercise of pilot authority. Following this screening, the sample contained 371 reports (186 glass, and 185 traditional). The almost equal dataset size occurred by chance.

Limitations of the Data

The data used in this study are solely based on ASRS incident reports. The ASRS database is the product of a voluntary reporting system where pilots, controllers, and others submit subjective accounts about safety-related aviation incidents. The ASRS program provides a limited waiver of disciplinary action to reporters who commit a violation (FAR 91.57). The reports contained in the database have several inherent limitations.

- The reports *cannot* be viewed as a random sample of the population of altitude deviations.
- The sample is merely a representation of what people report, and may contain reporting biases. Not all pilots are equally aware of, or willing to report to the ASRS program. Some may be more likely to report an incident that was already detected by another party (e.g., an air traffic controller).
- There are no means by which the *integrity* and factual correctness of the incident can be verified (Reynard, Billings, Cheaney & Hardy, 1986).
- Only those ASRS reports that have been subjected to the extensive analysis process and included in the database were used in this study.

Operators report what they want to report and what they subjectively believe is true. This is based on what is salient to them, their perspectives, and subjective biases. The absolute facts may be influenced by how candid pilots are in reporting their own involvement as well as their interrelations with other agents. Therefore, the data is confounded. However, the data represent what no laboratory or even a full mission simulation can ever duplicate—the real world.

Analysis

The goal of this research is to provide insight, in retrospect, as to the information, subsystems, and agents responsible for detecting an altitude deviation. Analysis conducted on this type of data can only be descriptive in nature. It would be inappropriate to assume that the sample necessarily characterizes all the attributes involved. However, some "strength" is gained by utilizing a large sample size. By partitioning the sample into two mutually exclusive datasets it may be assumed that the two datasets (glass and traditional cockpits), are alike except for the attribute used to divide them (since they were drawn using the same search strategy).

We have used exploratory data analysis techniques and contrasts to understand the datasets (Tukey, 1977). Our main objective in the analysis was to let the dataset speak for itself by revealing the composition of the sample. In several cases, contrasts were used to observe and test differences between categories and datasets. The factors that are coded under the “information and subsystem that helped restore safety” and “agent restoring safety” may not be mutually exclusive.

Only the information that was reported is known, and not what may have been omitted. We therefore acknowledge the fact that these specific contrasts may violate some statistical assumptions.

RESULTS

Triggering Information

The analysis of the traditional and glass datasets revealed the triggers that provided information for recovery. Figure 1 lists these triggers and their frequency within the sample. The stack-bar presents their tally in the glass and traditional datasets. Note that the overall height of each stack is the total number of occurrences for any given factor. For example, the Air Traffic Controller (ATC) stack details that there were 81 occurrences in which ATC restored safety involving glass cockpits and 99 occurrences involving traditional cockpits. Together they total 180 occurrences, which is the overall height of the ATC bar.

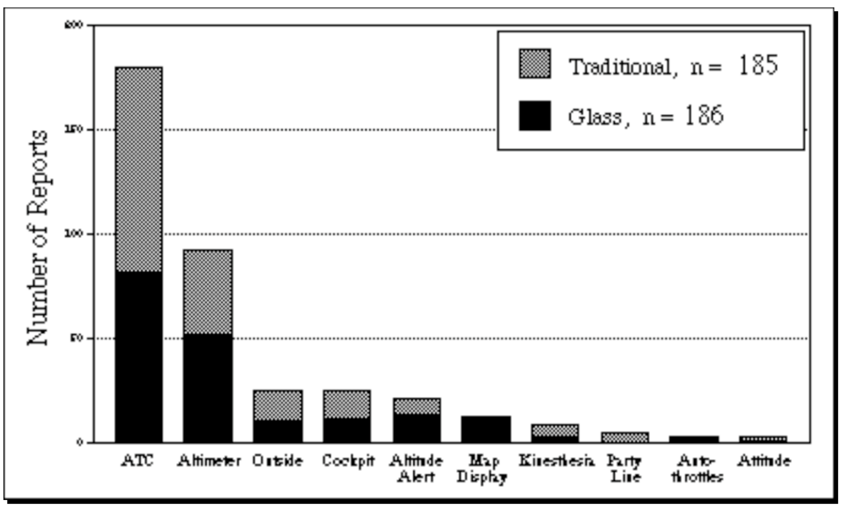


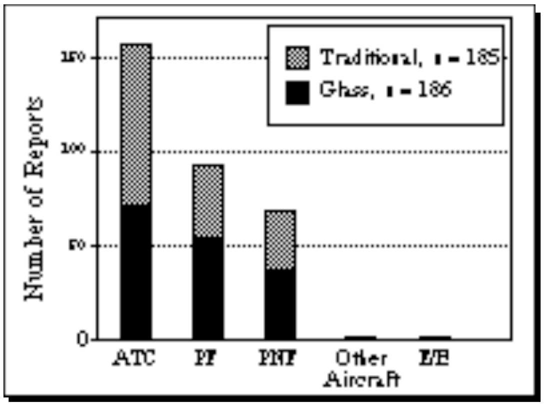
Figure 1. Triggers that provided anomaly detection

In addition to the primary trigger, several reporters indicated a secondary trigger that was pertinent for detection of an altitude deviation. The unique secondary triggers were: RMI/DME display, flight mode annunciator, stick shaker, airspeed indicator, vertical speed indicator, and engine instruments.

Agents' Duty and Position

Figure 2 depicts the distribution of agents detecting the anomaly in glass and traditional cockpits. Flight crew members were classified by their "duty," i.e., pilot flying (PF), pilot not flying (PNF), and flight engineer (F/E).

The contrast between "duty" and "cockpit type" (Figure 2), was significant ($p<.05$, X2=5.99, df=2). Subsequent chi-square tests indicated that the difference between "controller" and "flight crew members" (PF and PNF combined) accounted for this effect. In both glass and traditional cockpits, the PF was more likely to detect the altitude deviation than the PNF.



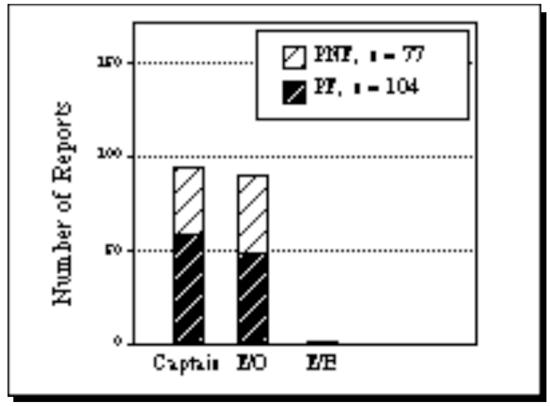


Figure 2. Agents' "duty"

Figure 3. Agents' "position"

Figure 3, depicts the distribution of flight crew members restoring safety by their "position," i.e., captain, first officer, and flight engineer. The stack bar presents their "duty" at the time of the incident.

Flight Phase

Figure 4 depicts the distribution of altitude deviations at the different flight phases (note that 10,000 feet is the arbitrary boundary between the "descent" and "approach" phases). The stack-bar presents the number of deviations involving glass and traditional cockpits for a given phase. The contrast between "flight phase" and "cockpit type" was significant (p<.001, X2=36.09, df=3).

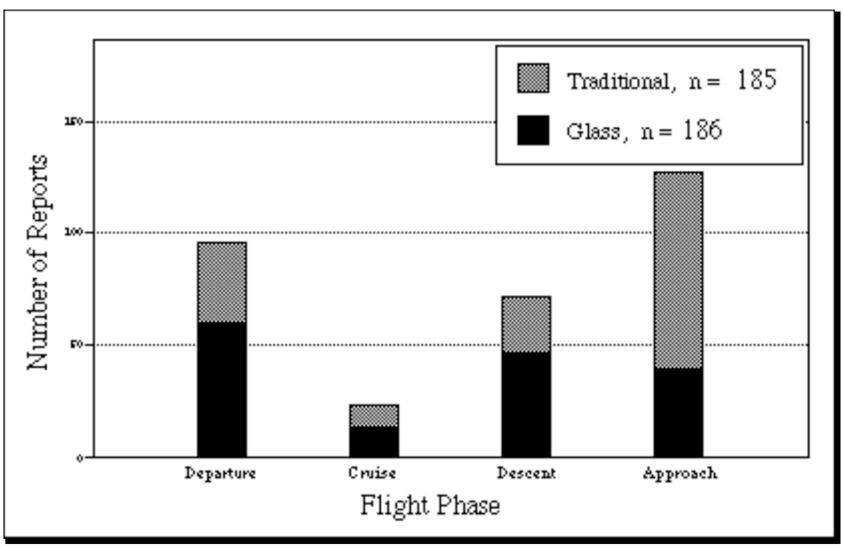


Figure 4. Flight Phase

Information Flow Model

A model that attempts to explain the flow of altitude information and ATC clearances was constructed based on an analysis of the first 150 reports (Figure 5). The model was then tested and validated on the remaining 350 reports. The model depicts the links, redundancies and feedback loops within the ground/air system with respect to altitude information. It also presents the subsystems associated with intent and state information as well as the sources of such information (ATC instructions, instrument procedures, FMC database, etc.).

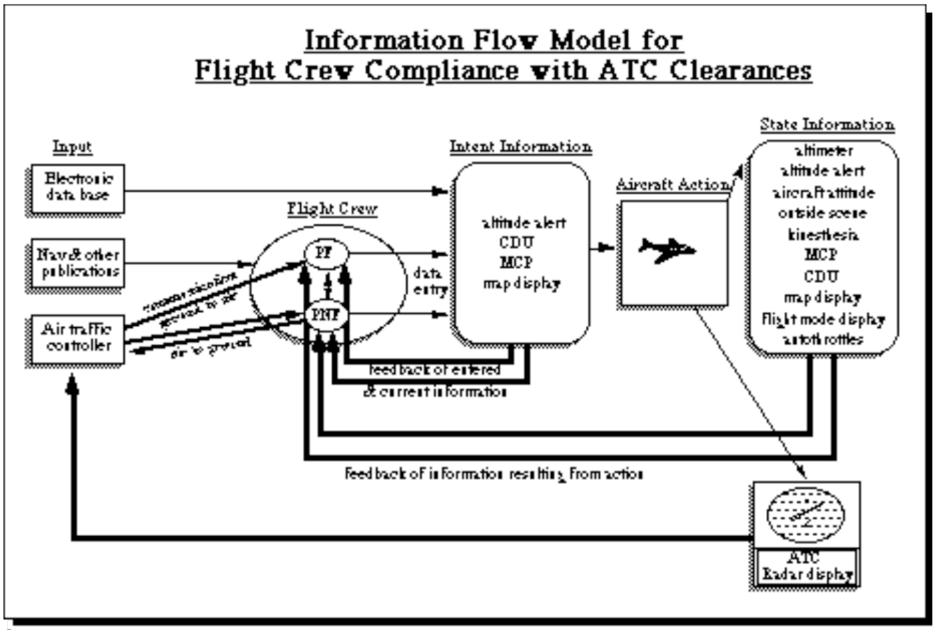


Figure 5. An information-flow model for altitude deviations

The structure and the interrelations between links, information, and subsystems depicted in the model can be used to track the flow of information and events leading to incidents. Its main purpose, however, is to depict the availability of altitude information and feedback loops along the progression of the event. This information is vital in order to detect, correct, and restore safety.

For example, report 143353 (NASA, 1991) details an incident that was described by both the controller and the flight crew. The pilots did not correctly hear the altitude clearance and the controller did not detect the erroneous readback. In this case, there was no correct altitude information in the cockpit. Therefore, the controller had the only feedback loop available in the system, i.e., when the inappropriate altitude of the aircraft was depicted on the radar display.

The following report narrative provides another example of unsuccessful information flow in a glass cockpit aircraft:

> Center gave us [a clearance to climb to] FL330. I asked the first officer to request FL290... This was approved, however FL330 was already in the altitude preselect and the first officer failed to reset it to FL290, and I missed it as I was telling “war stories” about my CRM class... The Center called us as we were climbing out of 30,500 feet and asked us where we were climbing to. (Report 142798)

In this case, the information was properly conveyed to the flight crew; however, the new intent information (FL290) was not entered into the altitude window of the autopilot system. Feedback loops from the altitude window and other cockpit instrumentations were available, but due to a distracting conversation, the comparison between intent and state information was not attended to. The controller saved the day by noticing the discrepancy between assigned altitude and the aircraft altitude displayed on the radar scope.

DISCUSSION

The methodology employed in this study proved useful in determining the agents and the triggering information for detecting altitude deviations. The list of triggers revealed several factors that come as no surprise: ATC, altimeter, and altitude alerter. Other factors were also found: outside view, map display, kinesthesia, autothrottles movement, aircraft attitude, and party line (Figure 1).

“Outside scene” emerged as the third-ranking trigger after “ATC” and “altimeter.” These incidents mostly involved familiarity of the flight crew with the geography of the terminal area and a comparison of the assigned altitude with the distance to the airport.

> Approach control set us up on 2700' for [a] back-course intercept outside of ATELL intersection, when normal ATELL intersection intercept is 4000' with FAF at 2700'. We started our descent to MDA after crossing ATELL... I think we confused ATELL for the FAF briefly. As PNF I was outside looking for airport and I felt like we were low and started rechecking the approach and asked F/O to stop descent. About that time approach asked us to recheck our altitude. We were about 1800' MSL. (Report 154085)

Cues from the “map display” (glass cockpits only) were mostly obtained by using the display to determine that a crossing restriction could not be met.

> Our clearance was to cross 40 miles north of SJU [at] 10,000'. The captain put the 40 DME waypoint in the FMC and armed the profile descent. We descended down the FMS descent path. I had my navigation display tuned to the long range so it was difficult to see at a glance what our distance was to the waypoint. I adjusted to the short range when we were leaving FL270 to see that we were only 15 miles from the waypoint. From this position it would have been impossible to make the restriction. (Report 143616)

Cues from the “autothrottles” (glass cockpits only) mostly involved unexpected throttle movement to the forward or idle position.

> While climbing through 5000' MSL, the autothrottles began to retard. As PF, I immediately pushed the autothrottle disengage switch... With no response from the captain and no obvious problem with the aircraft I re-engaged [the autothrottles]... Again the autothrottles began to retard somewhere between 7000' and 8000' MSL. I again disengaged and asked the captain why they were doing that. He then realized that the computer was following the SID to cross 7 DME from LAS at or below 7000' MSL. I then looked at my DME and it was 5.2 DME and we were between 8500' and 9000' MSL. (Report 148950)

Triggering information obtained from monitoring the radio communications to other aircraft was coded as “party line.”

> While cruising at 13,000 feet on a flight from MYR to RDU, Center cleared our flight to descend to 12,000'... Approximately 20-30 seconds later Center cleared

> [another] company aircraft to descend to 12,000' and they acknowledged their clearance. Because of the similarity of the call signs our F/O asked Center to confirm our clearance to descend to 12,000'. At this time Center directed us to maintain 13,000'. We stopped our descent immediately and returned to 13,000 feet. (Report 146694)

Surprisingly, “altitude alerters” did not account for many detections of altitude anomalies. It may be that this factor is confounded with the “altimeter,” since in many ways the two subsystems are integrated. Perhaps the altitude alert is alerting crews in a timely manner and preventing the altitude deviation. Kinesthesia, or “seat of the pants,” involved situations in which flight crews felt a motion cue that enabled them to detect the anomaly. “Attitude” involved situations in which the aircraft changed pitch for various reasons.

About half the altitude deviations were detected by the air traffic controller (180 controller, 191 flight crew). The information flow model can be used to explain one of the factors that may account for this finding. If the flight crew failed to receive or the controller failed to convey the correct altitude assignment, the controller is usually the only agent capable of comparing state information with the correct altitude assignment. Another factor, related to the waiver of disciplinary action, is the fact that flight crews may be more likely to report a deviation if ATC is aware of it. This finding, nevertheless, is consistent. An ASRS study of altitude alert systems dating back to 1978 indicated that, in 56% of the cases, “an air traffic controller first noticed the altitude deviation” (NASA, 1978).

As for the information that was available in both cockpit types, e.g., altimeter, altitude alert, outside scene, kinesthesia, attitude, and party line, there were surprisingly few differences between the glass and traditional cockpits; this may imply that the basic detection process of an altitude deviation is common in both cockpits. Figure 1 indicates that additional triggering information for detecting altitude deviations is available in glass cockpits. However, the autoflight systems in these aircraft present an additional set of complex interactions.

Figure 2 indicates that there was a unique interaction between the agent detecting the anomaly (controller and flight crew) and the type of cockpit. It appears that glass-cockpit flight crews detect more deviations than their counterparts in traditional cockpits, while controllers tend to detect more deviations involving traditional cockpits.

Figure 3 and the statistical contrasts indicated that there were no significant differences between the “position” which the flight crew held (captain, first officer) and detection of altitude deviations. This held true regardless of their “duty” (PF, PNF) or cockpit type (glass, traditional).

Figure 4 indicates that most altitude deviations occur during climb and descent. These, naturally, are the phases in which altitude and track clearances are constantly changed. In most cases, the rate of receiving new clearances increases as the aircraft descends toward the airport. As one would expect, the data depict that the majority of the altitude deviations and successful recoveries occurred during the “approach” phase, i.e., from 10,000 feet to landing. The significant statistical contrast indicated a unique interaction between flight phase and cockpit type. Glass cockpits were more likely to be involved in an altitude deviation during the “departure” phase (takeoff to top of climb) and “descent” phase (top of descent to 10,000 feet); whereas traditional cockpits were much more likely to “bust” an altitude below 10,000 feet—an environment characterized with constant altitude and heading changes.

The information-flow model for altitude deviations can be used to explain the progression of events and the recovery path from such incidents. We believe this model may aid cockpit designers and those establishing operating procedures to (1) safeguard and promote those redundancies and feedback loops that are positively detecting anomalies; (2) identify and strengthen weak links in the current system; and (3) to provide a scheme for anticipating the potential advantages as well as disadvantages of new subsystems (e.g., data link).

In conclusion, this study represents a different approach to understanding an aspect of aviation safety through the analysis of incident reports. The general methodology for understanding the factors enabling recovery may be applicable to a variety of other aviation safety problems, e.g., track deviations or near mid-air collisions. From the current study, a systematic study of anomaly detection could be undertaken through an ASRS structured callback (Orlady & Wheeler, 1989) and laboratory simulation. This study should not be viewed as definitive work, but rather as a first step in determining what information on the flight deck provides the necessary cues to “save the day.”

ACKNOWLEDGMENTS

This project was conducted as part of the NASA Aviation Safety and Automation Plan. The authors gratefully acknowledge the support of the ASRS office for this study. Elizabeth Parker-Haney, Marc T. Pittman, and Connie L. Williams helped in data entry and producing the graphics. The authors thank Sandra C. Lozito, Daniel Morrow, Robert E. Schrader, Leon Segal, Richard J. Tarrel, and Earl L. Wiener for reviewing this paper and providing helpful comments. Michael S. Hayes was supported in part by the Air Line Pilots Association and Delta Air Lines. Asaf Degani was supported by Grant NCC2-237 from NASA Ames Research Center to the San Jose State University Foundation.

REFERENCES

Billings, C. E., & Cheaney, E. S. (1981). *The information transfer problem in the aviation system* (NASA Technical Paper 1875). Moffett Field, CA: NASA Ames Research Center.

Billings, C. E., Grayson, R., Hecht, W., & Curry, R. E. (1980). *A study of near midair collision in U.S. terminal airspace* (Quarterly Report 11, NASA Technical Memorandum 81225). Moffett Field, CA: NASA Ames Research Center.

Degani, A., & Wiener, E. L. (1990). *The human factors of flight-deck checklists: The normal checklist* (NASA Contractor Report 177549). Moffett Field, CA: NASA Ames Research Center.

Lyman, E. G., & Orlady, H. W. (1981). *Fatigue and associated performance decrements in air transport operations* (NASA Contractor Report 166167). Moffett Field, CA: NASA Ames Research Center.

Monan, W. P. (1979). *Distraction—A human factor in air carrier hazard events* (NASA Technical Memorandum 78608, p. 2-23). Moffett Field, CA: NASA Ames Research Center.

Monan, W. P. (1988). *Human factors in aviation operations: The hearback problem* (NASA Contractor Report 177398). Moffett Field, CA: NASA Ames Research Center.

National Aeronautics and Space Administration (1978). *Human factors associated with altitude alert systems* (Sixth quarterly report, NASA Technical Memorandum 78511). Moffett Field, CA: NASA Ames Research Center.

National Aeronautics and Space Administration (1991). *EFIS and standard cockpit anomalies* (Special Request 1964 [Database search]). Moffett Field, CA: NASA Ames Research Center.

Orlady, H. W. (1982). *Flight crew performance when pilot flying and pilot not flying duties are exchanged* (NASA Contractor Report 166433). Moffett Field, CA: NASA Ames Research Center.

Orlady, H. W., & Wheeler, W. A. (1989). Training for advanced technology aircraft. *Proceedings of the Fifth International Symposium on Aviation Psychology* (pp. 91-96). Columbus, OH: The Ohio State University.

Reynard, W. D., Billings, C. E., Cheaney, E. S., & Hardy, R. (1986). *The development of the NASA aviation safety reporting system* (NASA Reference Publication 1114). Moffett Field, CA: NASA Ames Research Center.

Schwartz, D. (1990). Reducing the human error contribution to mishaps through identification of sequential error chains. *Safetyliner* (pp. 13-19). Denver, CO: United Airlines.

Sumwalt, R. L. (1991). Eliminating pilot-caused altitude deviations: A human factors approach. *Proceedings of the Sixth International Symposium on Aviation Psychology*. Columbus, OH: The Ohio State University

Thomas, R. E., & Rosenthal, L. J. (1982). *Probability distribution of altitude deviations* (NASA Contractor Report 166339). Moffett Field, CA: NASA Ames Research Center.

Tukey, J. W. (1977). *Exploratory data analysis*. Reading, MA: Addison-Wesley.

Wiener, E. L. (1977). Controlled flight into terrain accidents: System-induced errors. *Human Factors, 19*, 171-181.

Wiener, E. L. (1989). *The human factors of advanced technology ("glass cockpit") transport aircraft* (NASA Contractor Report 177528). Moffett Field, CA: NASA Ames Research Center.